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INFLUENCE OF HEAT TREATMENT ON THE STRUCTURE AND PROPERTIES OF Ti–28Al–7Nb–2Mo–2Cr TITANIUM ALUMINIDE AND ITS WELDED JOINTS

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ABSTRACT

The influence of furnace annealing on the structure of cast metal in ingots of 200 mm diameter of the intermetallic Ti–28Al–7Nb–2Mo–2Cr titanium alloy produced by the method of electron beam melting and its welded joints produced by the method of electron beam welding was determined. It was determined that the EBM metal produced from the ingots of 200 mm diameter is satisfactorily welded under the conditions of applying such additional technological measures as preheating and local heat treatment. It is shown that annealing at the temperature of 1260 °C for 10 h led to the formation of a uniform microstructure in the base metal, HAZ and weld metal, decomposition of the duplex structure and absence of regions with a two-phase ($\gamma+\alpha_2$)-lamellar structure. The room temperature strength of welded joints after annealing is equal to 746 MPa or 98 % of the base metal strength.

KEYWORDS: titanium aluminide, electron beam welding, welded joints, duplex structure, lamellar structure, strength

INTRODUCTION

Intermetallic alloys based on Ti–Al system have high indices of heat-resistant properties and are designed for operation in different structures at temperatures of 600–900 °C [1, 2]. In such alloys, two intermetallic phases are formed: α_2-phase (Ti_3A1), which has a hexagonal densely-packed crystalline lattice, and γ-phase (TiAl), which has an ordered tetragonally distorted face-centered structure. Gamma-alloys are divided into two large groups: single-phase γ-alloys with the aluminium content of 50–52 mol.% and two-phase ($\alpha_2+\gamma$) alloys with the aluminium content of 42–49 mol.%. Most common alloying elements in such alloys are Nb, Cr, Mo, Zr, Mn, W [3–6]. Gamma-alloys are considered to be the most promising materials for aerospace and engine-building areas [7–11].

The prospects for the use of intermetallics are based on the following features of intermetallics: intermetallics preserve their strength to high temperatures [12–14]; the modulus of elasticity of intermetallics is less intensively reduced with an increase in the temperature unlike that of industrial heat-resistant alloys; the self-diffusion coefficient in intermetallics is by several orders of magnitude lower than that in disordered alloys at comparable temperatures, which affects the lower creep rate [15, 16].

The use of alloys based on titanium intermetallics for the manufacturing of turbine blades, as well as hot gas tract parts such as combustion chambers, diffusers, exhaust systems, will allow increasing the operating temperature of gas turbine engines (GTE) by 100–150 °C, reducing mass and increasing the service life of engine. In Ukraine, in nowadays conditions, the manufacturing and application of this class of materials for the aircraft and power engineering is of great demand [16].

The main tasks to be solved in the development of structural materials based on intermetallics are an increase in the low-temperature ductility and fracture toughness [18].

To produce alloys based on titanium aluminides, the use of electron beam melting (EBM) is promising, which allows minimizing the liquation processes during ingot solidification by dividing the process of melting billet and ingot solidification, producing high-quality homogeneous ingots with a fine-grained structure and removing high- and low-density inclusions, which is very important for producing ingots of critical purpose [17, 18].

Also, an important problem affecting the possibility of using alloys based on titanium aluminide is their weldability. The thermal cycle of electron beam (EBW) and argon-arc welding (AAW) leads to the formation of cold cracks in joints [19]. To prevent the formation of cracks, it is necessary to apply additional technological measures — local heat treatment (LHT), preheating and annealing after welding [20–24]. The impact of heat treatment on the properties of welded joints, produced by EBW with LHT is also a poorly-studied issue.

The aim of this work is to determine the impact of furnace annealing on the base metal structure of the intermetallic Ti–28Al–7Nb–2Mo–2Cr titanium alloy, produced by the EBM method, and its welded joints produced by the method of electron beam welding.

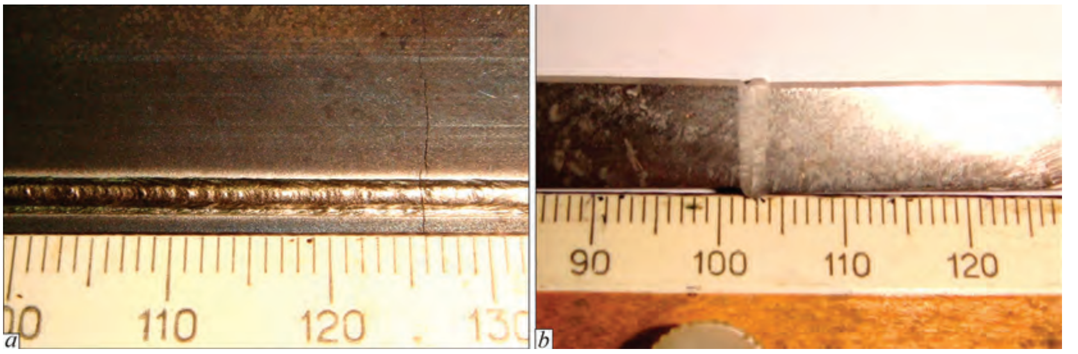

Figure 1. Welded joint of alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, produced by EBW without using preheating and LHT (*a*) and in the state after LHT (*b*): I_b = 90 mA (*a*), V_w = 7 mm/s (*a*, *b*), LHT temperature is 750 °C, 10 min (*b*)

MATERIALS AND RESEARCH METHODS

Smelting of experimental ingots with a diameter of 200 mm from the alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide was carried out in the multipurpose laboratory electron beam installation UE-121.

Examination of the specimen structure of the alloys based on titanium aluminide was carried out in the Neophot-32 optical microscope at various magnifications. The photos of microstructures were taken with a digital camera C-3000 of the OLYMPUS Company.

EBW was carried out in the modernized welding unit UL-144, equipped with ELA 60/60 power source, TsF-19 welding gun and SU-220 beam control device [25].

EBW allows applying such additional technological measures as preheating and postweld local heat treatment directly in a vacuum chamber that prevents oxidation and saturation of the weld metal and heat-affected zone (HAZ) by gas impurities [26–28]. To determine weldability of the specimens from the metal based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, welding of 120×60×8 mm specimens was performed. For electron beam welding, billets for the specimens were cut out of the cast ingot of 200 mm diameter. The specimens of butt joints were assembled without a gap and edge preparation.

One of the advantages in electron beam welding technology concerning titanium and Ti-based alloys, in addition to providing reliable protection of welded joints, is the ability to carry out local preheating and further heat treatment in a vacuum chamber [29]. Preheating of welded joints is a quite effective technological measure used in welding of high-strength titanium alloys to prevent the formation of cold cracks [26, 30].

EBW parameters are the following: speed — 7 mm/s; current — 80 mA. Temperature of specimen preheating was 400 °C, temperature of postweld LHT in the vacuum chamber — 900 °C. The use of preheating and local electron beam heat treatment allowed producing high-quality welded joints without cracks. The temperatures of preheating of 400 °C and postweld LHT in the vacuum chamber of 900 °C were chosen in accordance with the experience of welding 47XD alloy based on titanium aluminide [31].

Welded joints of the alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, produced without LHT, are prone to the formation of cold cracks (Figure 1, *a*). When applying such additional technological measures as preheating and LHT, the metal of Ti–28Al–7Nb–2Mo–2Cr titanium aluminide is welded satisfactorily. The weld formation in EBW of Ti–28Al–7Nb–2Mo–2Cr titanium aluminide with preheating and LHT is good, undercuts, pores and cracks are not formed.

An example of the welded joint transverse macrosection of the alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, produced by EBW with preheating and postweld LHT is shown in Figure 1, *b*. It was determined: the width of the weld above is 2.2 mm and on the back side it is 1.8 mm, the height of the reinforcement above is 0.5 mm and on the back side it is 0.8 mm. The weld formation in EBW with preheating and postweld LHT is good, undercuts, pores and cracks are not formed.

STRUCTURE OF BASE METAL OF ALLOY BASED ON Ti–28Al–7Nb–2Mo–2Cr TITANIUM ALUMINIDE

γ-TiA1 intermetallic, on the base of which an experimental intermetallic Ti–28Al–7Nb–2Mo–2Cr alloy was produced, has an ordered tetragonally distorted face-centered structure L10, in which planes filled with titanium atoms alternate with planes occupied by aluminium atoms [32]. The homogeneity region of this intermetallic in the Ti–Al system is quite large [33].

Microstructure of the base metal of the intermetallic alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide is shown in Figure 2. In the middle zone of the ingot, the cast metal is characterized by the fact that the linear phase is an ordered cubic B2-phase forming a mesh structure with different sizes of meshes from 30 to 100 μm (Figure 2, *a*), sometimes against

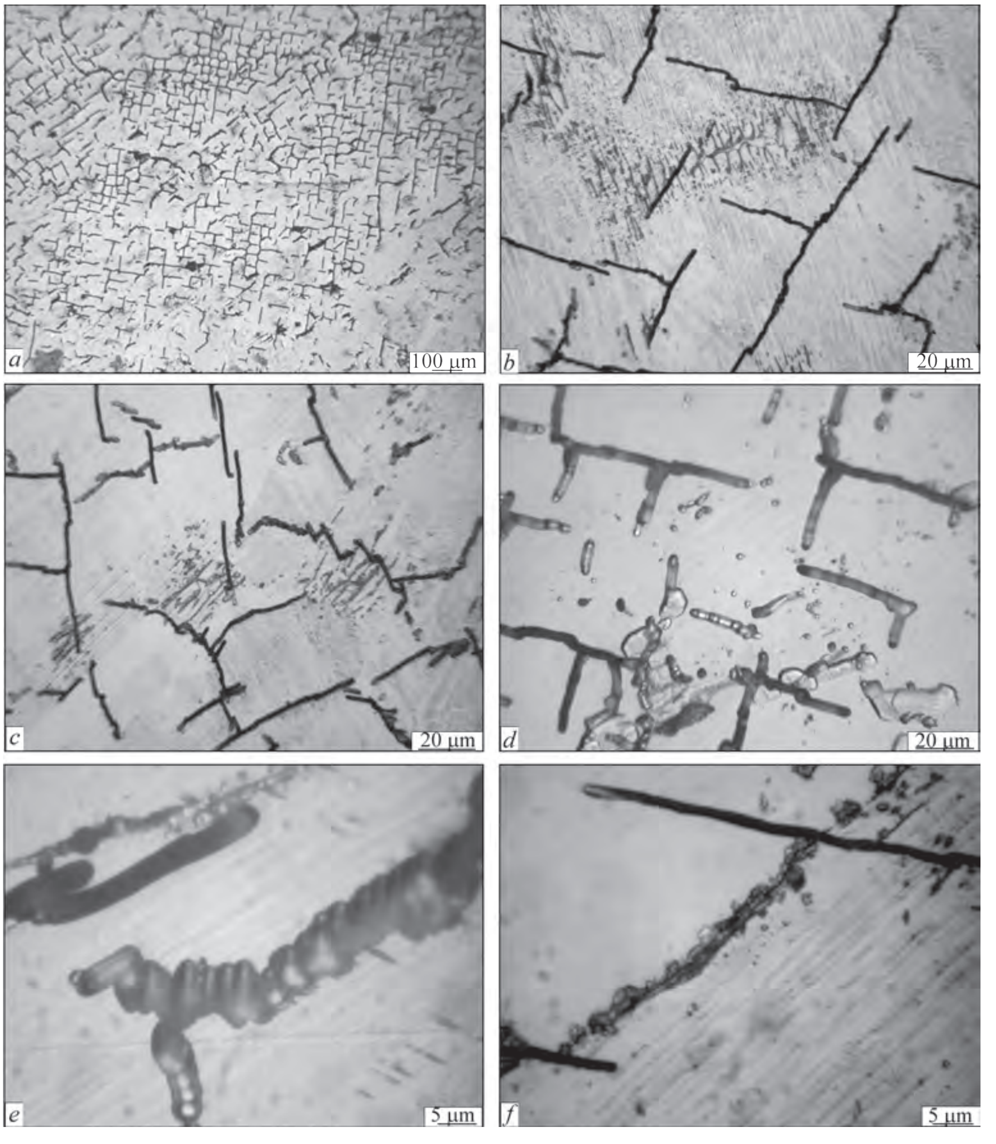

Figure 2. Microstructure of base metal of alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide

the background (Figure 2, *b*) of lamellar structure with lamellae twinning (Figure 2, *f*). In some places, a light phase containing other particles is observed (Figure 2, *b*). The phase forming a mesh structure includes both rectilinear and curvilinear regions (Figure 2, *c*) and looks dark or light in the photo (Figure 2, *d*). Often, such particles have a transverse substructure (Figure 2, *e*). Dispersed precipitations (probably, precipitations of B2-phase) are located both against the background of the matrix phase (Figure 2, *d*), as well as decorate other components of the structure: grain boundaries, lamellae (Figure 2, *c*). The thickness of the linear phase forming a mesh ranges from 1 to 5 μm (Figure 2, *e*).

To determine the influence of additional furnace heat treatment, namely annealing, on the structure of the base metal of Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, a part of the metal was subjected to furnace annealing. Annealing was performed in the vacuum chamber, its temperature was 1260 °C, the time was 10 h, cooling of the joints occurred with the furnace. The BM structure after annealing is represented by a light matrix phase, which is γ-titanium aluminide (Figure 3, *a*). Against the background of the matrix, a dark linear phase is clearly revealed, which forms a mesh with nuclei of 50–100 μm. The thickness of the linear phase elements is 1.5–2.5 μm.

After annealing, the structure also contains dispersed particles of up to 1.0–1.5 μm, forming clusters (Figure 3, *b*) in the matrix phase, as well as chains decorating other structural elements (boundaries of lamellae and other particles) (Figure 3, *c*, *d*). In the structure, also separated dark (Figure 3, *d*) and light particles of 2–15 μm long and about 2 μm thick are present.

Thus, all structural elements inherent in the metal of Ti–28Al–7Nb–2Mo–2Cr titanium aluminide after annealing were observed in the metal structure before annealing as well. A significant difference of annealed BM from non-annealed is a significant reduction in the fraction of a lamellar structure. Thus, as

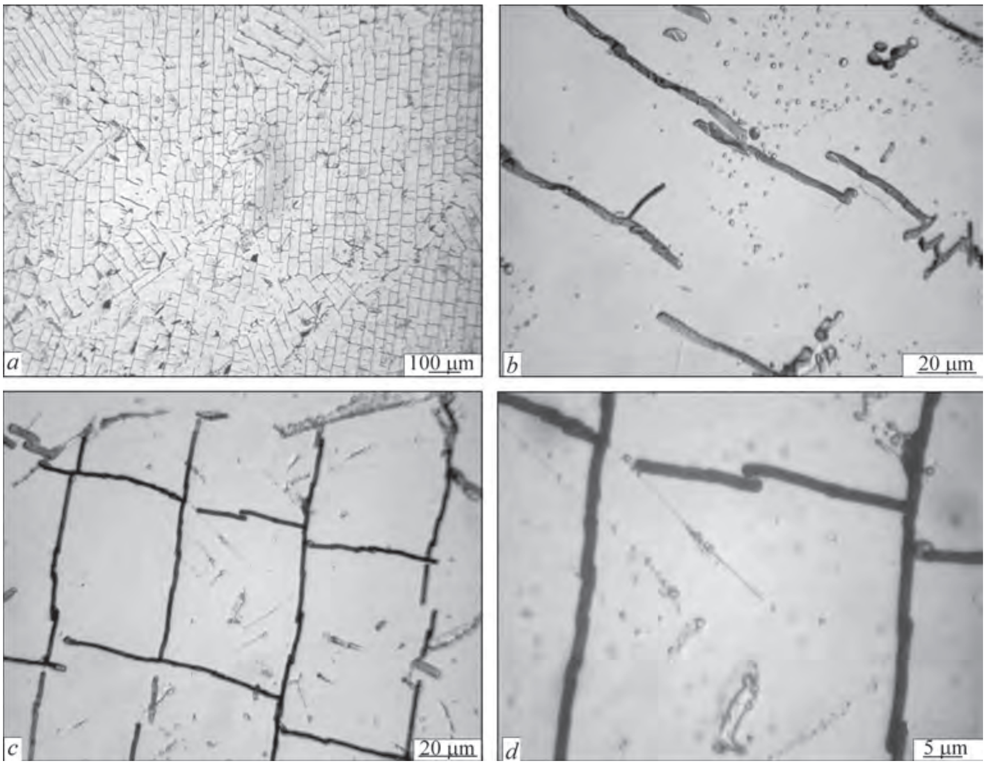

Figure 3. Microstructure of base metal of alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, after annealing at 1260 °C

a result of annealing at 1260 °C, in the base metal of Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, transformation namely of the duplex structure occurred.

MICROSTRUCTURE OF WELD METAL

The weld metal, produced by EBW with preheating and LHT, consists mainly of coarse grains, elongated in the direction of heat removal. Only along the weld axis, finer equiaxial grains of 100–200 µm are formed. The linear dark phase forming a mesh is located in the form of bands transverse to the weld axis in the weld part of medium height. The intragranular metal structure of the middle weld part consists of small (not more than 20 µm) regions with a lamel-

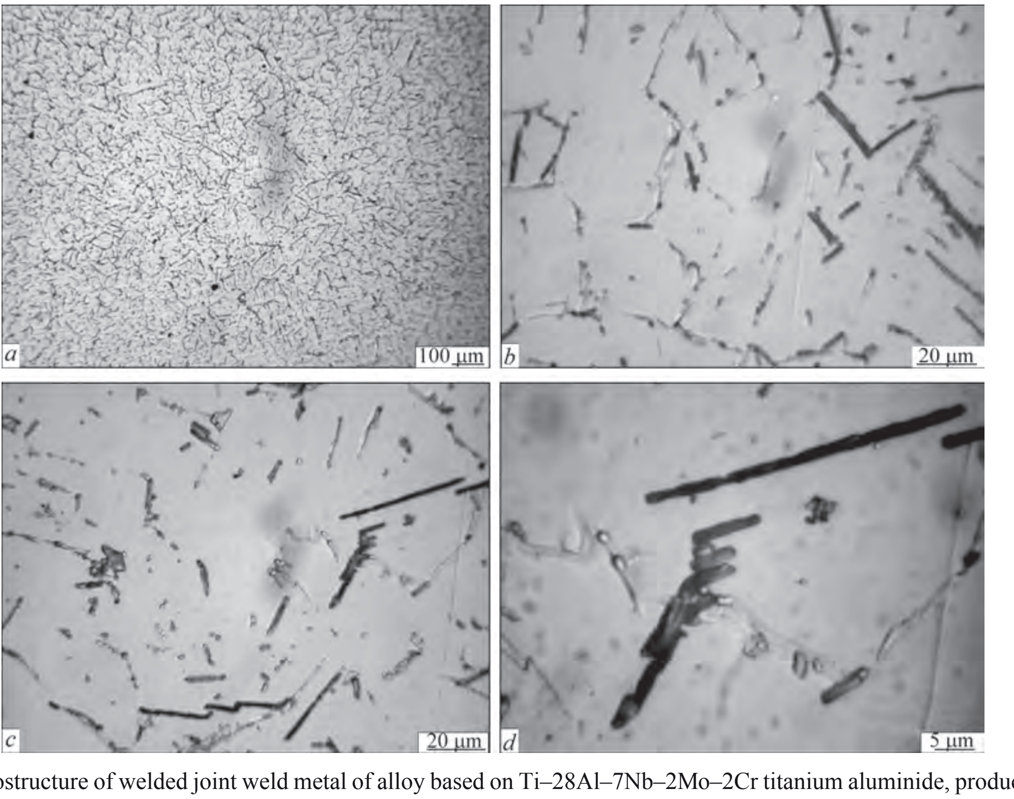

Figure 4. Microstructure of welded joint weld metal of alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, produced by EBW, after annealing at 1260 °C

lar structure against the background of a light matrix phase. Here, the thickness of lamellae in the weld metal is about 1 μm. In addition, in the structure, linear particles forming a mesh are present. They have a length of 3–80 μm and a thickness of 1–3 μm, can be homogeneous and fragmented. In many linear particles, dispersed phase precipitations are concentrated, which are arranged also against the background of the matrix phase. The weld metal structure contains also micropores, their size is 1–2 μm.

MICROSTRUCTURE OF WELD METAL AFTER HEAT TREATMENT

In the weld metal against the background of the light matrix phase, linear dark and light structural elements are revealed (Figure 4). Dark particles, mostly rectilinear of up to 50 μm long and 1.5–2.5 μm thick are located in the volume of grains (Figure 4, *b*, *c*). Light rectilinear particles are often decorated with dispersed precipitations, along the grain boundaries, light fringing can be observed (Figure 4, *d*). Dispersed particles of up to 2 μm are present both in the volume of grains as well as in the form of boundary fringes or other structural elements. In the weld metal, micropores are present.

In the weld metal, produced by EBW after 10-hour annealing at 1200 °C as well as in the base metal, lamellar structure observed before annealing, is absent.

MICROSTRUCTURE OF HAZ METAL

HAZ microstructure of the welded joint of Ti–28Al–7Nb–2Mo–2Cr titanium aluminide unlike BM in HAZ is represented by a lamellar structure with a small length of lamellae of up to 10 μm and a thickness of about 1 μm. From the weld metal, the metal of the near-weld zone differs by much lower density of region location with a lamellar structure. Other structural HAZ components are identical to similar elements of the weld metal structure except of

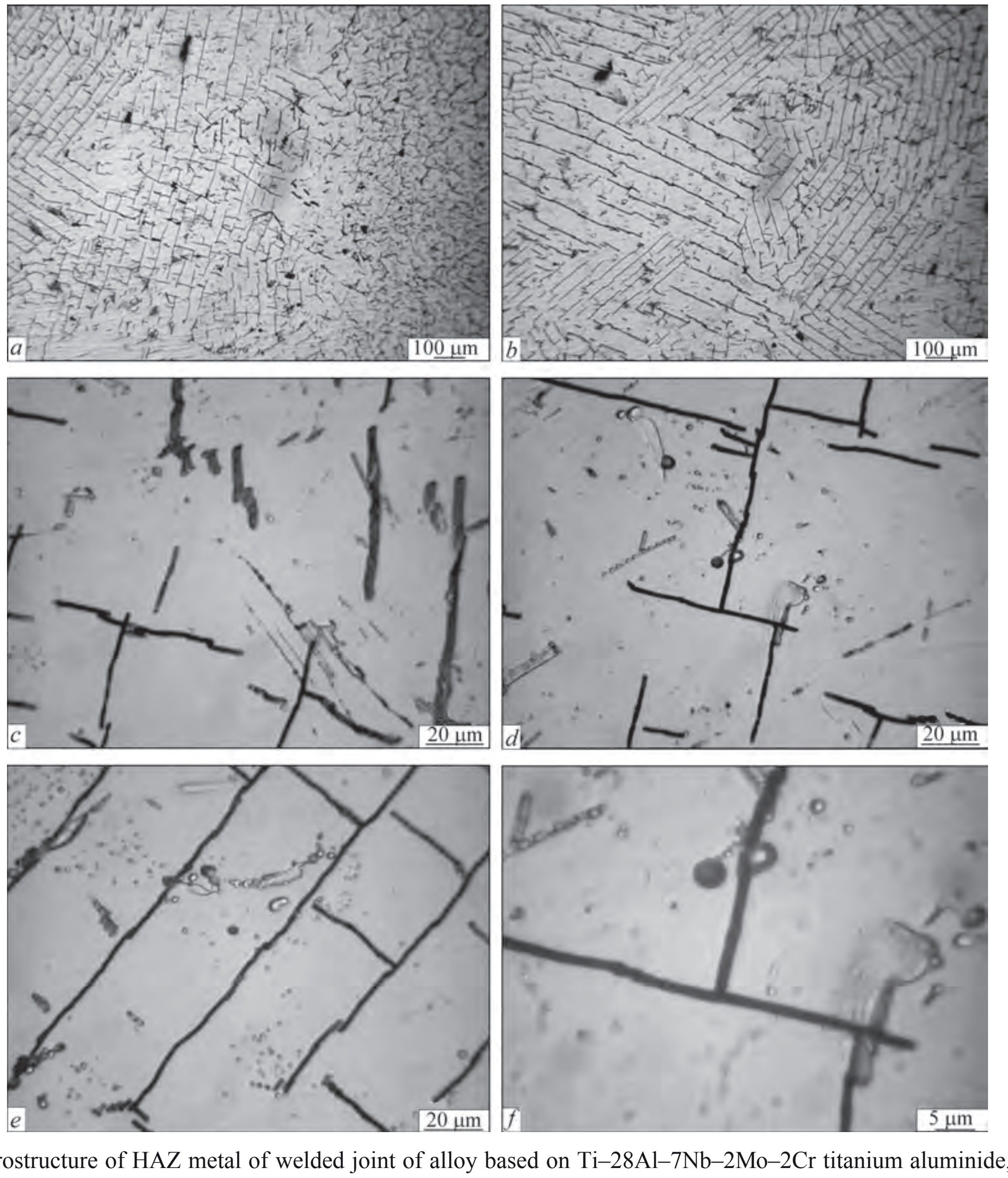

Figure 5. Microstructure of HAZ metal of welded joint of alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, produced by EBW, in the state after annealing at 1260 °C

Table 1. Mechanical properties of base metal and welded joints of alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, produced by EBW with preheating and LHT

Specimen	σ_t, MPa	σ_{02}, MPa	*KCV*, J/cm^2
Base metal	754	570	12.9
EB welded joint after annealing at 1260 °C during 10 h	746	566	9.8

the fact that in HAZ, the phase forming a mesh structure does not form bands transverse to the weld axis and, most probably, inherits the nature of the phase location forming a mesh in BM.

Microstructure of the HAZ metal after annealing at 1260 °C is presented in Figure 5. Analysis of the obtained images showed that in HAZ, up to the very fusion zone, a formation of a linear dark phase of a mesh pattern is observed, which in some places changes into a banded pattern. The parameters of the mesh and bands nuclei are the same as in BM. The thickness of the linear phase is 1.0–2.5 μm. In the HAZ metal, light particles of up to 20 μm long are encountered (Figure 5, *d*, *b*), which are often decorated with dispersed particles. In addition, single dispersed particles and their clusters are observed (Figure 5, *e*, *f*).

Thus, the main difference of the HAZ metal structure of the welded joint of the intermetallic Ti–28Al–7Nb–2Mo–2Cr alloy after annealing consists in the absence of regions with a lamellar structure that were present in HAZ after welding.

Therefore, the carried out 10-hour annealing of the electron beam welded joint of the intermetallic alloy based on γ-phase at a temperature of 1260 °C led to the formation of relatively homogeneous microstructure in the base metal, HAZ and weld metal. As a result of annealing, in the metal of all zones of the welded joint, decomposition of a duplex lamellar structure occurred. In the metal of all areas of the welded joint, regions with a lamellar structure are almost absent.

The obtained mechanical properties of welded joints of the alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide allowed making a conclusion that at 20 °C, the strength of welded joints after annealing at 1260 °C is at the level of 746 MPa or 98 % from the strength of the base metal (Table 1). The indices of impact toughness are at the level of 9–13 J/cm^2.

Thus, the cast metal of ingots based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide, produced by the EBM method is satisfactorily welded by EBW when applying preheating and LHT. After 10-hour annealing of the base metal and welded joint metal of the intermetallic alloy at a temperature of 1260 °C in the base metal, weld metal and HAZ, relatively uniform microstructure was formed. As a result of annealing, in the metal of all zones of the welded joint, decomposition of a duplex lamellar structure occurred. In general, the maximum fracture toughness is typical of alloys with a lamellar structure, but after heat treatment, welded joints have indices of the room temperature strength at the level of the base metal. In the metal of all areas of the welded joint, regions with a lamellar structure are almost absent.

CONCLUSIONS

1. The metal produced from the ingots based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide is satisfactorily welded by EBW under the conditions of applying such additional technological measures, as preheating and LHT. The weld formation in EBW with preheating and postweld LHT is good, undercuts, pores and cracks were not detected.

2. The intragranular structure of the weld metal after AAW and EBW with LHT is different from the structure of the base metal. Thus, in EBW it is composed of small (not more than 20 μm) regions with a ($\gamma+\alpha_2$)-lamellar structure against the background of a light matrix of the γ-phase with a mesh from linear particles of 3–80 μm long and 1–3 μm thick, in AAW — from a single-phase γ-structure, alternating with the regions of a two-phase ($\gamma+\alpha_2$)-lamellar structure of up to 50 μm.

3. Annealing of the welded joint of Ti–8Al–7Nb–2Mo–2Cr alloy, produced by EBW, at a temperature of 1260 °C during 10 h led to the formation of a homogeneous microstructure in the base metal, HAZ and weld metal, as a result of annealing in all zones of the welded joint, decomposition of a duplex structure occurred and the regions with a two-phase ($\gamma+\alpha_2$)-lamellar structure are absent.

4. The strength of welded joints, produced by EBW with LHT of the intermetallic alloy based on Ti–28Al–7Nb–2Mo–2Cr titanium aluminide after annealing at 1260 °C is at the level of 746 MPa or 98 % from the strength of the base metal.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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